RELIABILITY OF FLOW-CONTROL SYSTEMS

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BC hydro

FOR GENERATIONS

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TIMELINE

BESc (2007-2011)

- Undergraduate research position after 2nd and 3rd year with Professor Simonovic

MESc (2011-2012)

- Continuation of work in undergraduate research

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TIMELINE

BC Hydro (2013-Present)

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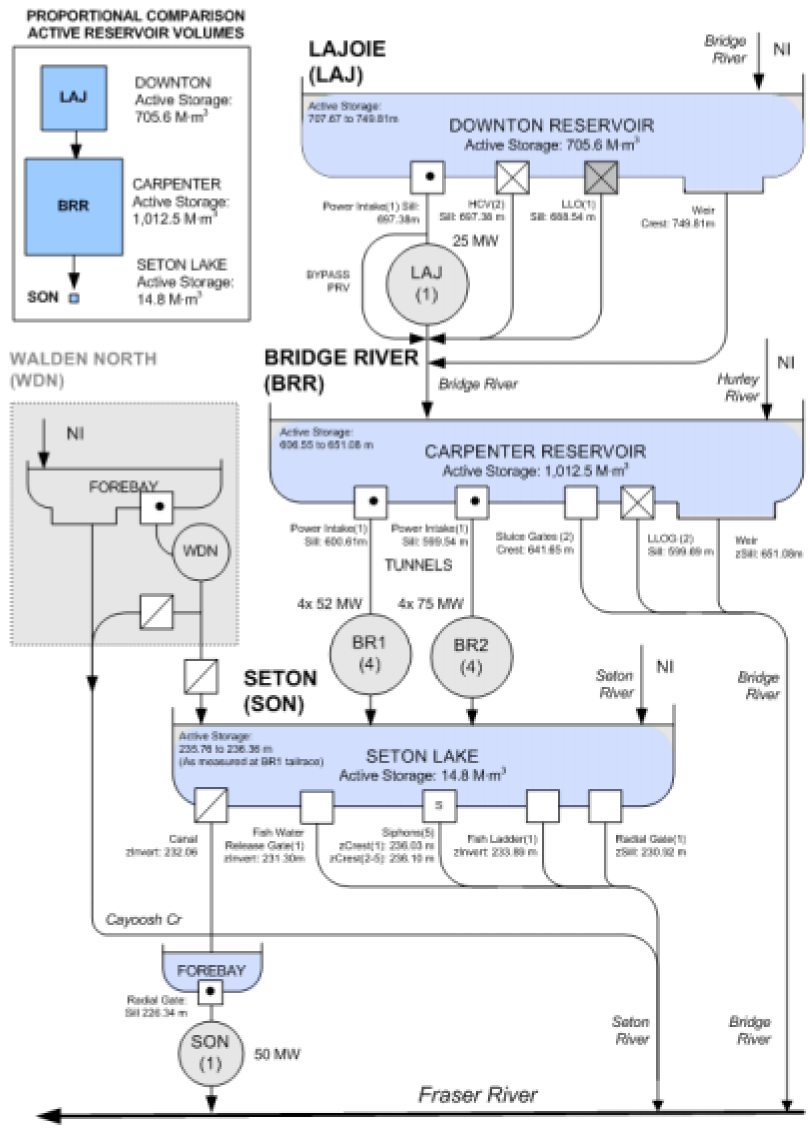
BRIDGE RIVER



LAJOIE DAM

BC Hydro (2013-Present)

DAM SAFETY

Do we need a new approach?

DAM SAFETY

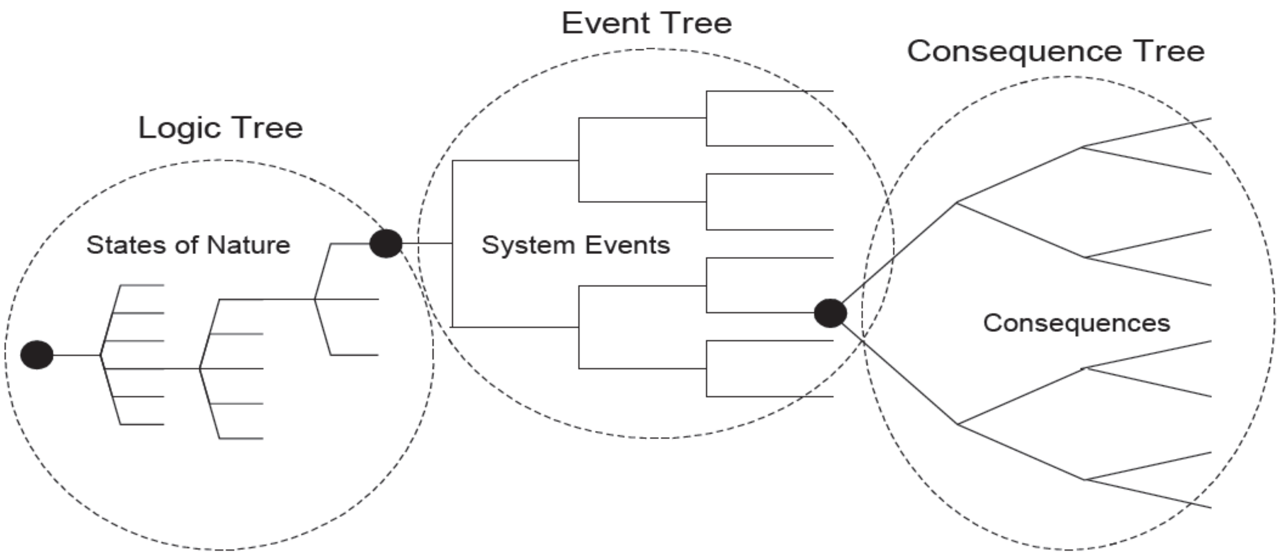
BC Hydro Fleet

- All dams built between the early 1900s and 1985
- Many assets reaching end-of-life
- Major capital investment plan to renew generation infrastructure
- New methodology for risk assessment of dam systems required?

PROBABILISTIC RISK ASSESSMENT (PRA)

Current standard for dam safety analyses

- Events are assumed to be independent (eg. flood, gate failure, landslide)
- Linear analysis using a chain of events
- Quantify the likelihood of identified failure modes
- No consideration of human factors (eg. maintenance, design errors)



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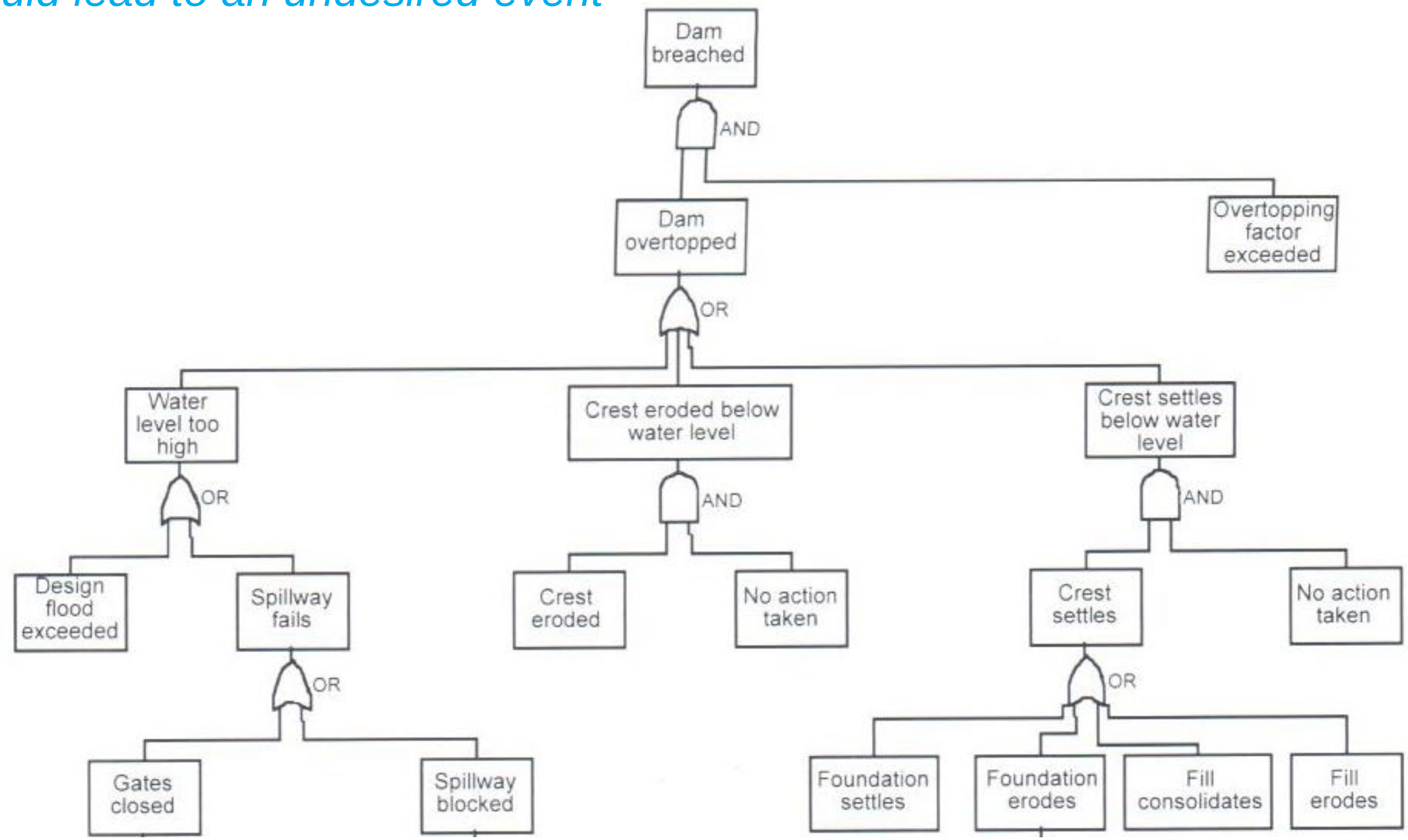
FAULT TREE ANALYSIS

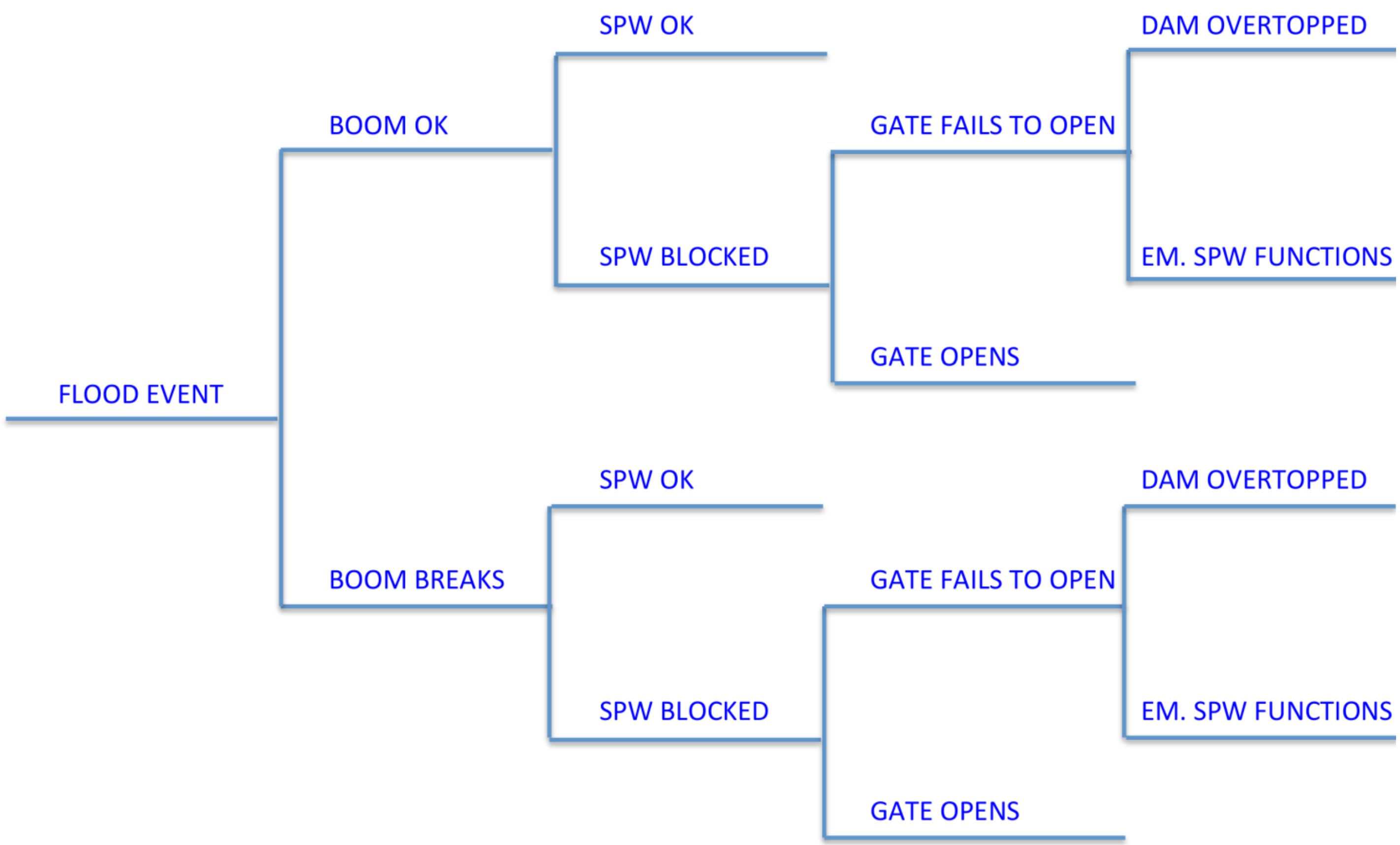
A fault tree shows the interaction among system elements whose failure could lead to an undesired event



Ref: G. Baecher

EVENT TREE ANALYSIS

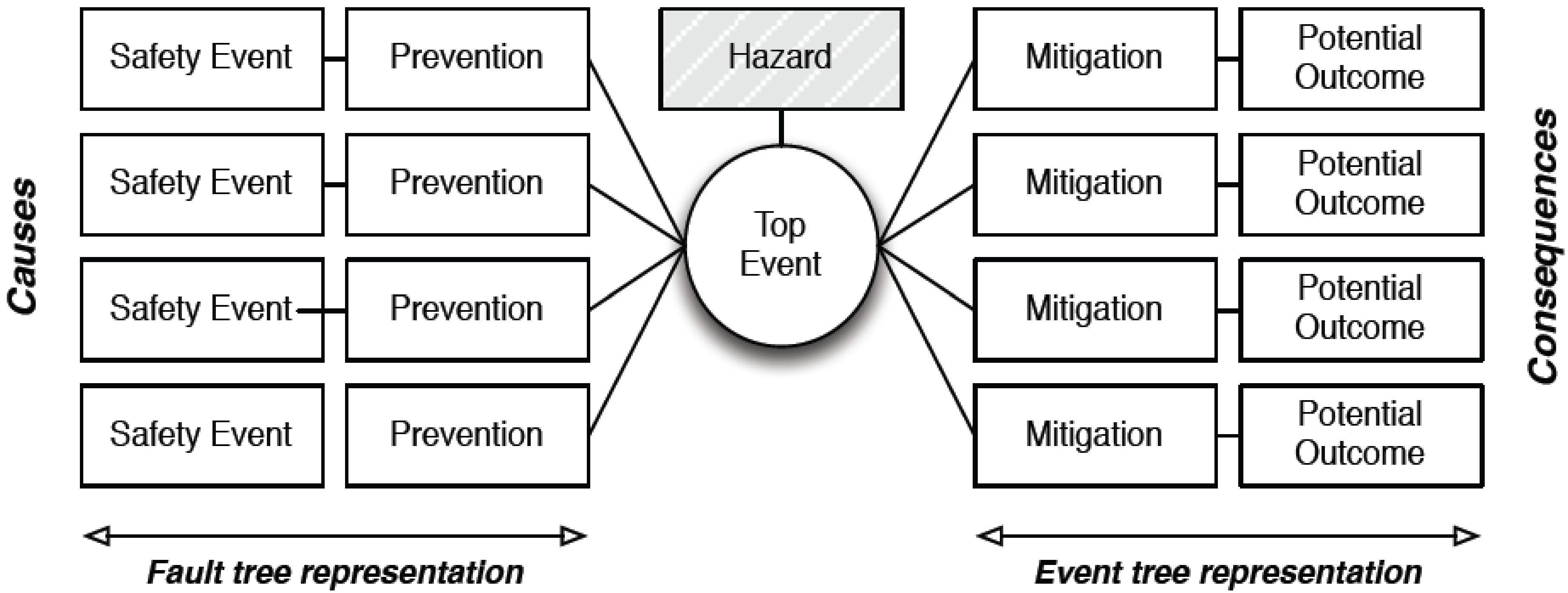
An event tree graphically shows the logical sequence of events given the occurrence of a specific circumstance



Ref: G. Baecher

BOW-TIE MODEL

The bow-tie model is a method that can be used for risk management pertaining to a specific event (total or component failure). Key event causes and ways to prevent them are identified. Strategies for mitigation of the potential event outcomes are identified.



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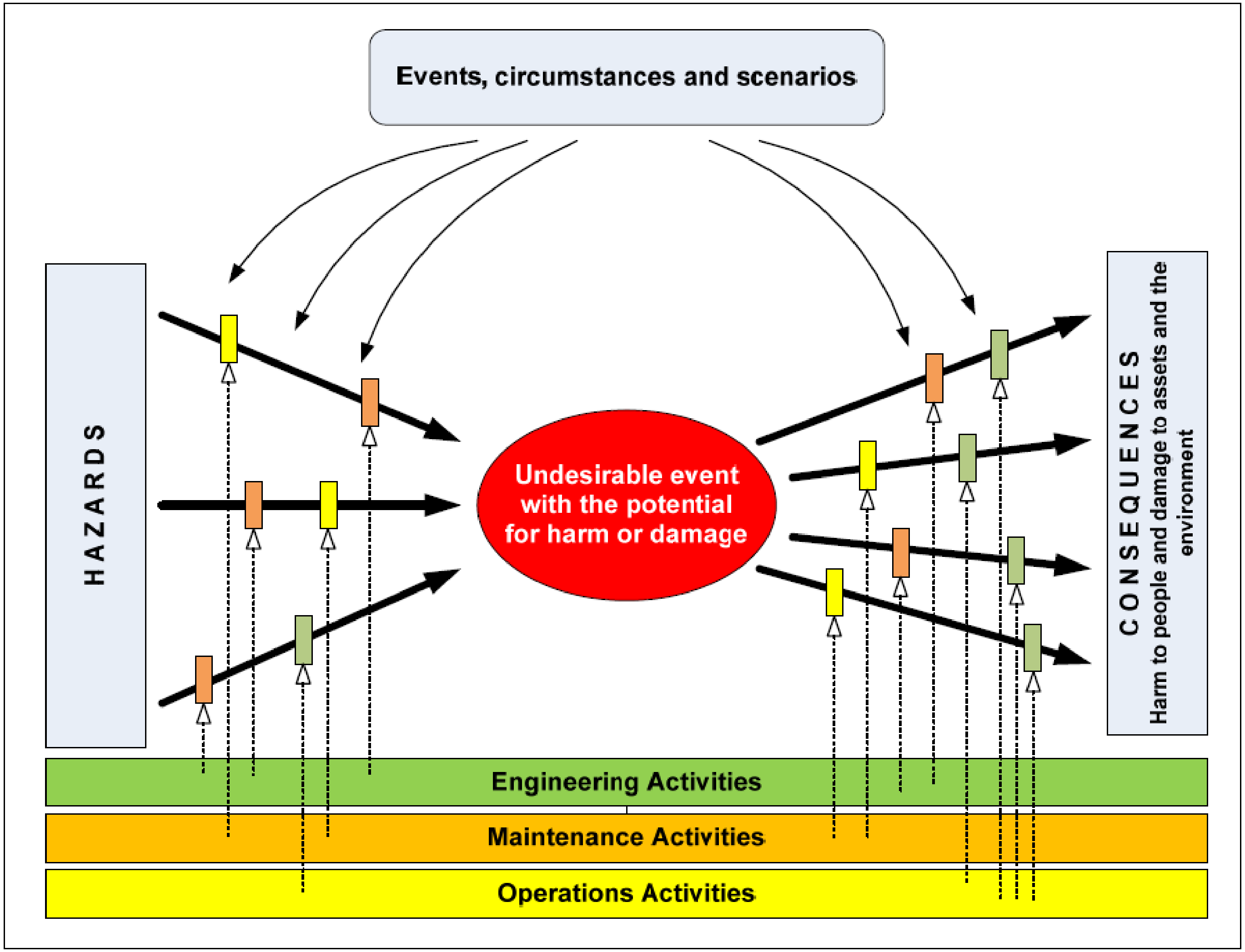
BOW-TIE MODEL



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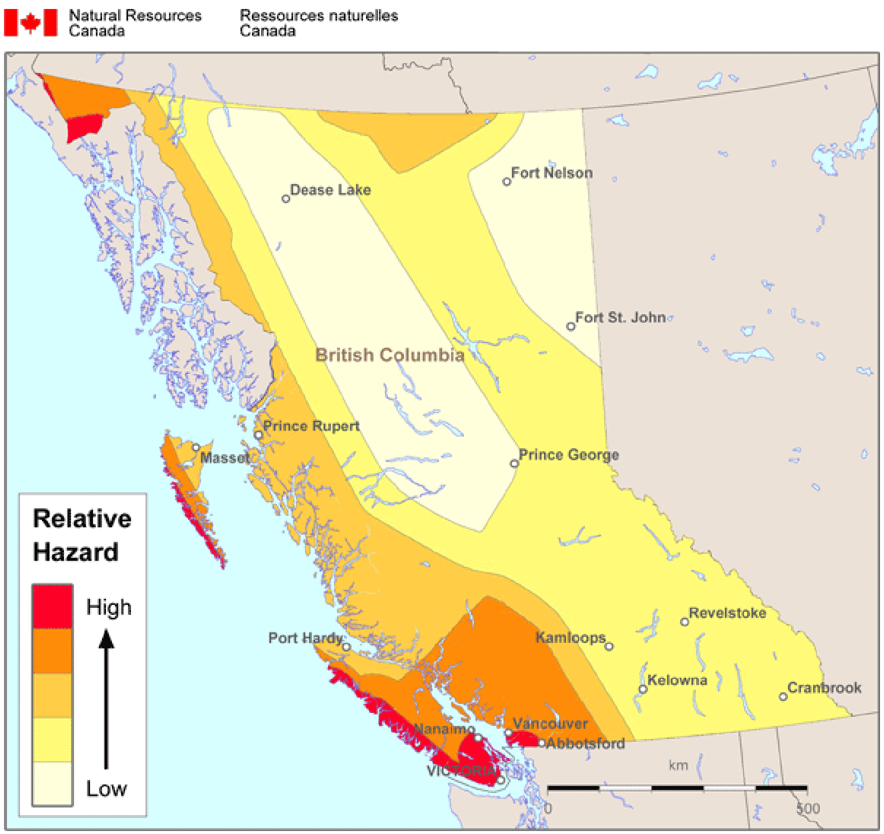
EXTREME EVENT ANALYSIS



Probable Maximum Earthquake

Probable Maximum Flood

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PROBABILISTIC RISK ASSESSMENT (PRA)

Successes:

- Brainstorming of various failure modes
- Extreme load events and checks against design criteria
- Analysis of linear events

Observation:

- Many historical dam failures are caused by events which are well within the design envelope of the system
- Uncommon combination of common events
- Nonlinearities, feedbacks, component interactions in complex systems
- Lack of understanding of the system behaviour over time

TAUM SAUK, 2005

Pumped storage dam overtopping

- Gauge readings too low
- Back-up gauges located too high to indicate imminent failure
- No visual monitoring
- No overflow spillway

Failure of SCADA (Supervisory control and data acquisition) systems and oversight of design engineers

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Ref: P. Regan, G. Baecher

SAYANO-SHUSHENSKAYA, 2009

Hydroelectric plant turbine failure

- Turbine operated in a “rough load zone” on several occasions
- Head cover bolt fatigue
- Inadequate maintenance or inspections?
- Lack of turbine shutoff valves and no backup power for intake gates

Failure resulting from design omissions, operator oversight and inadequate maintenance or inspections

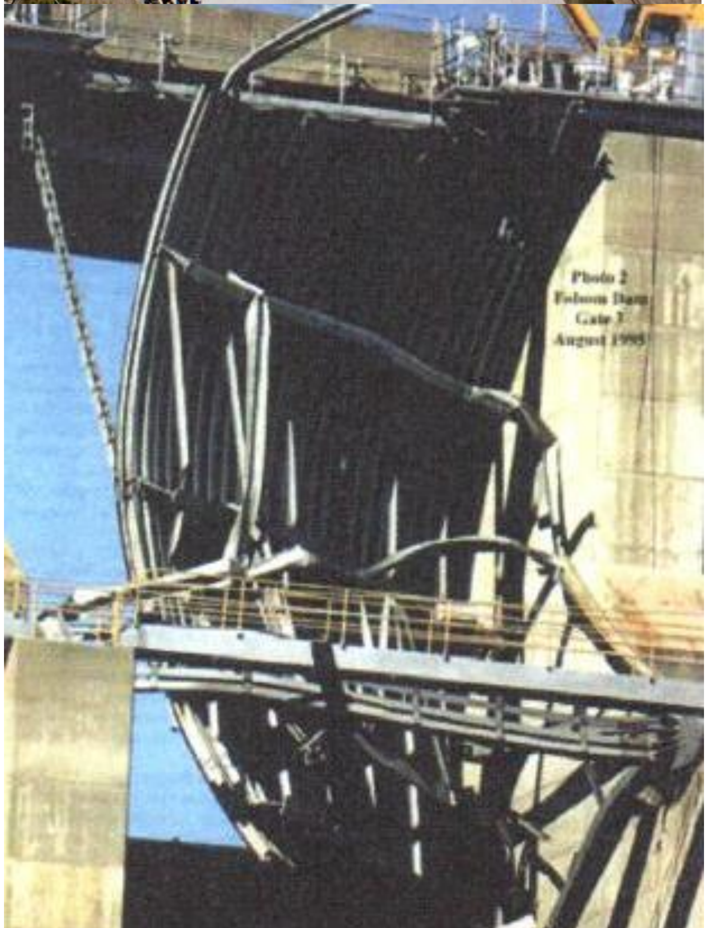
Ref: P. Regan

FOLSOM DAM, 1995

Hydroelectric plant spillway gate failure

- Corrosion at the pin-hub interface increased the bending stress causing yielding of the strut
- Decreasing frequency of inspection, testing and maintenance
- Inadequate lubricant specifications
- Lack of sensors to measure force applied to move gate

Failure resulting from increasing corrosion, inadequate maintenance and inspections, design omissions (lubricant, sensors)



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Ref: G. Baecher

NOPPIKOSKI DAM, 1985

Hydroelectric plant dam breach

- High inflow event, not well forecasted
- Failure of spillway gate hoist
- Inability to access remote dam site to open additional gates
- Not able to activate emergency gate (lack of personnel/equipment on site)
- Lack of backup power supply
- Lack of staff to respond to crisis

Failure resulting from design omissions and operational issues

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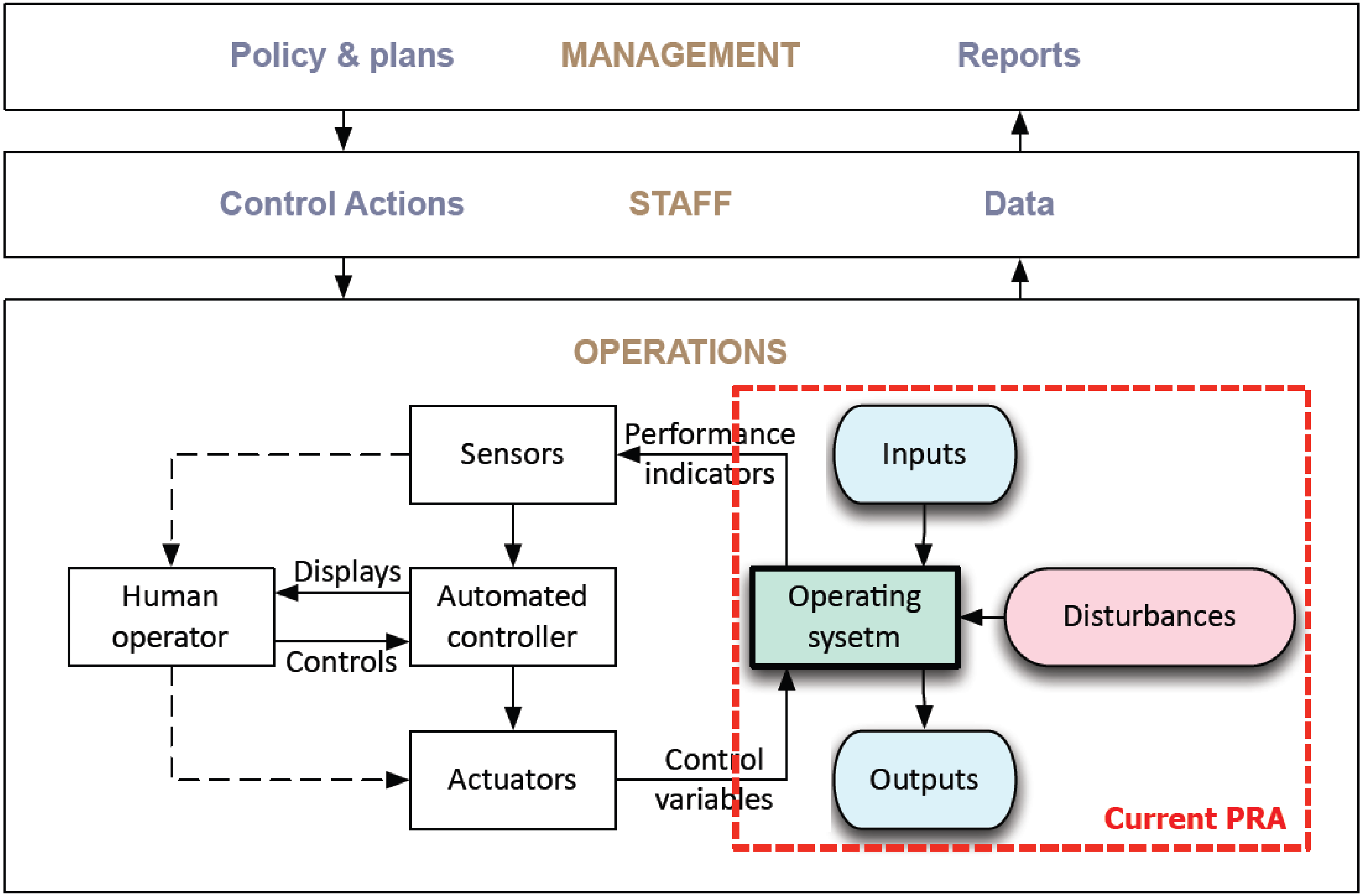
Ref: P. Regan, G. Baecher

A NEW APPROACH TO RELIABILITY ANALYSIS



Adapted from Leveson, 2010 , Baecher, 2014

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A NEW APPROACH TO RELIABILITY ANALYSIS

Requirements:

- Nonlinear capabilities
- Assess combinations of loadings
- Design and construction errors
- Human factors (operational errors etc.)
- Uncertainties
- Disturbances
- Maintenance Activities
- Evolution of the system over time

SYSTEM DYNAMICS SIMULATION

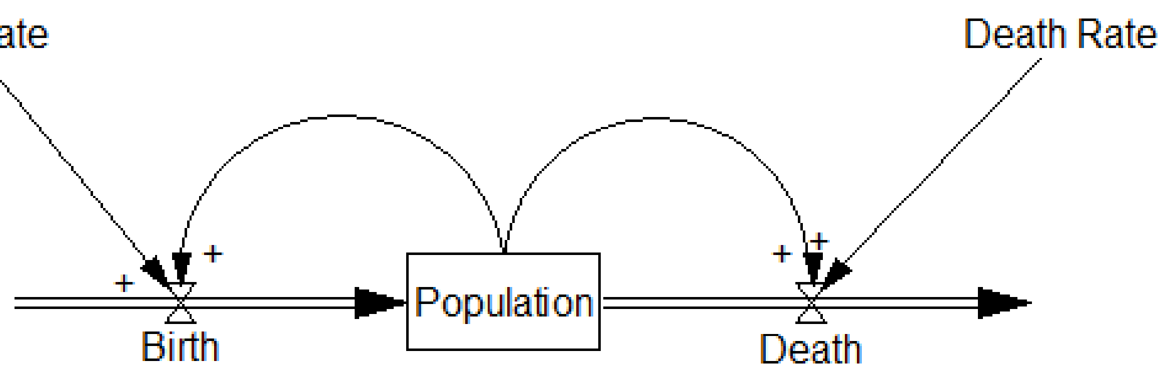
Advantages:

- Simulation can be useful in showing how a system changes over time
- Nonlinearities can be simulated using feedback loops, stocks and flows
- Ability to represent non-physical system components
    - Operations
    - Maintenance
    - Budget
    - Information flow
    - Disturbances (eg. Flood events, earthquakes, landslides, debris buildup, forced outages, sabotage)

SYSTEM DYNAMICS SIMULATION

The basics:

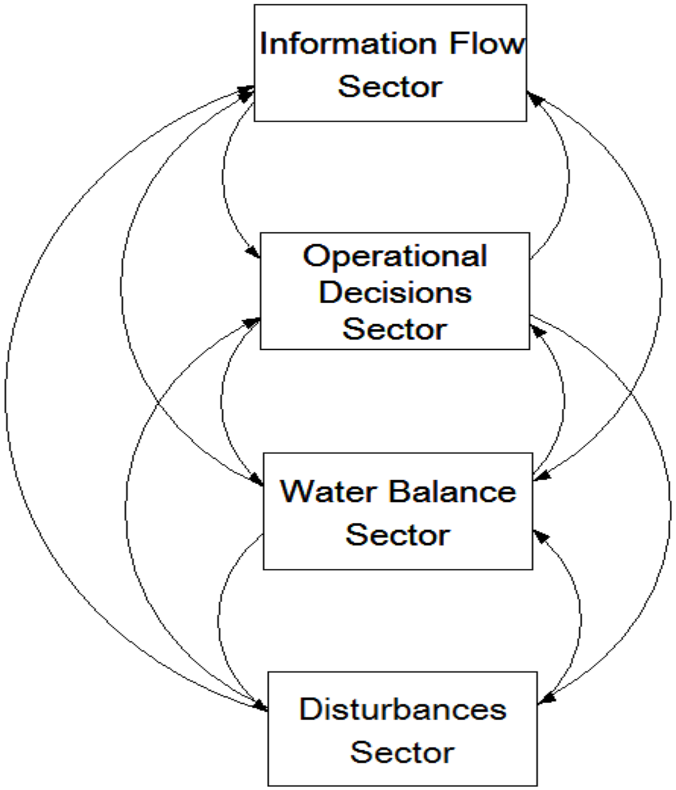
- Stocks accumulate in value (eg. population)
- Flows describe the rate of change in the stock at a given time step (births, deaths)
- Auxiliary variables can be constants or equations which relate to other variables and help describe system behaviour (birth rate, death rate)



SYSTEM DYNAMICS SIMULATION

Model setup:

- Several sectors will be required to deal with different system aspects
  - Water-balance
  - Operations
  - Information flow (SCADA)
  - Disturbances
- System-of-systems approach?
- Sensitivity analysis required to deal with uncertainties



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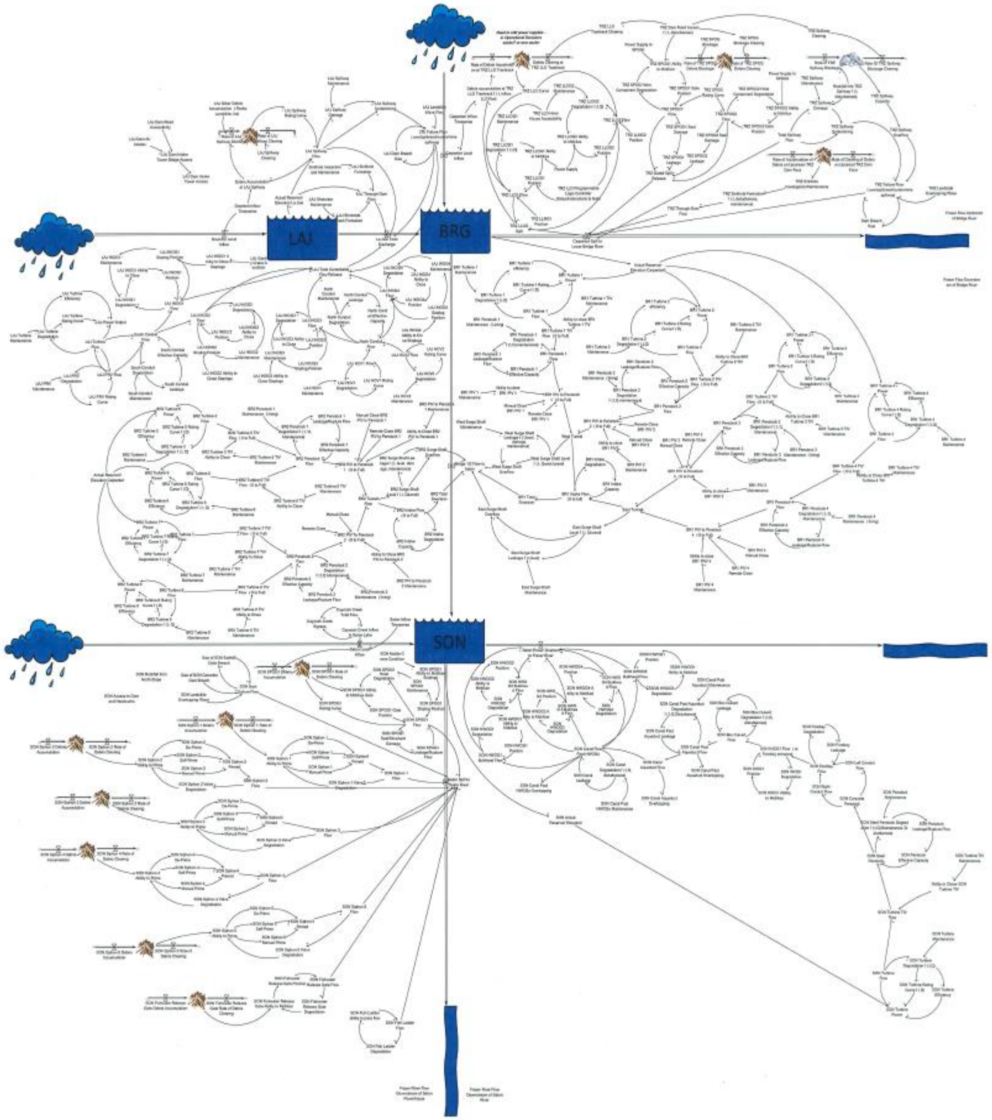
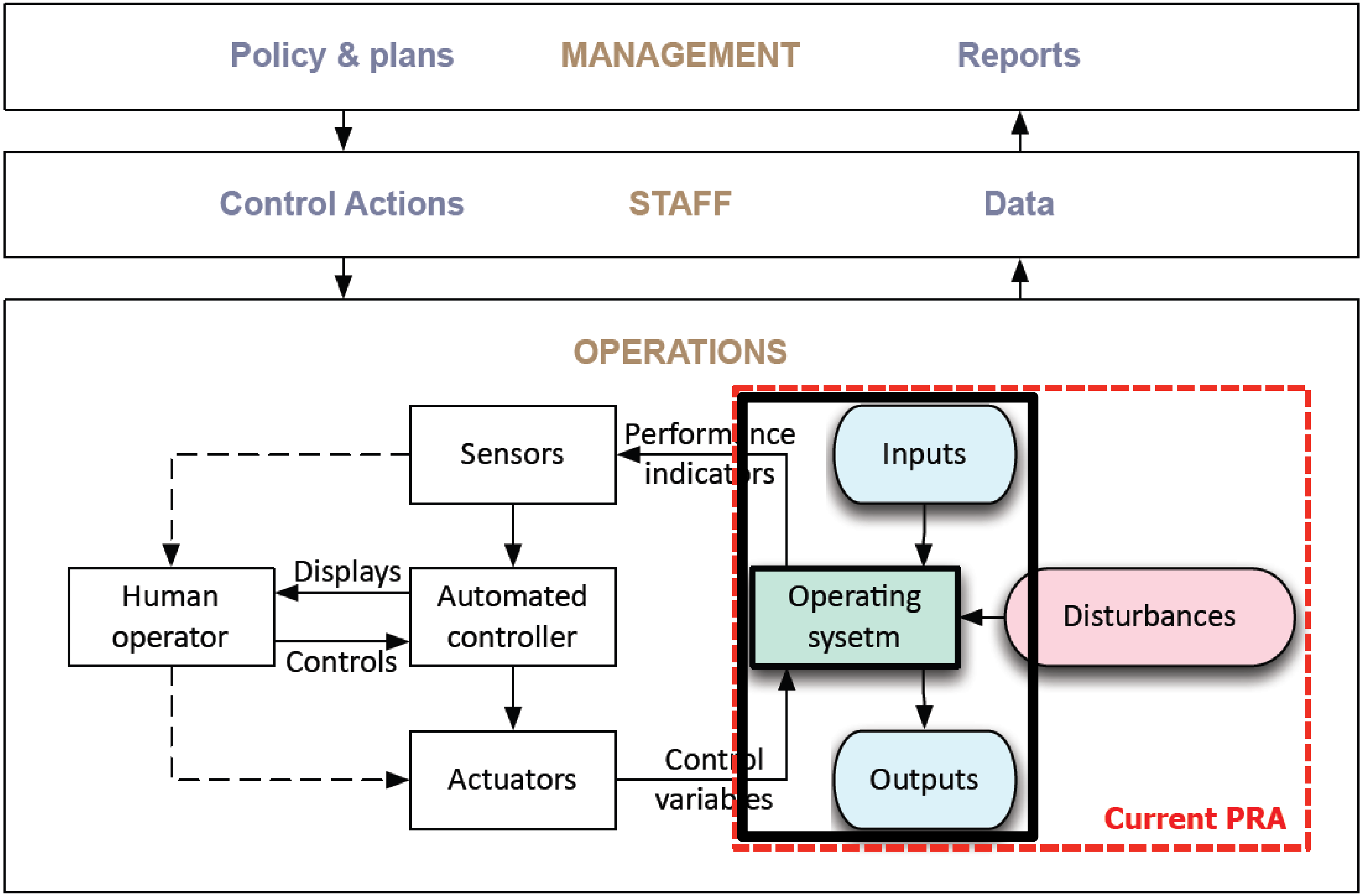
SYSTEM DYNAMICS SIMULATION

Water-Balance Sector:

- Physical structures which pass, store, or divert water for power production
- Component conditions (degradation, age)
- Component conditional reliability functions
- Site accessibility
- Back-up electrical systems and operational modes



SYSTEM DYNAMICS SIMULATION



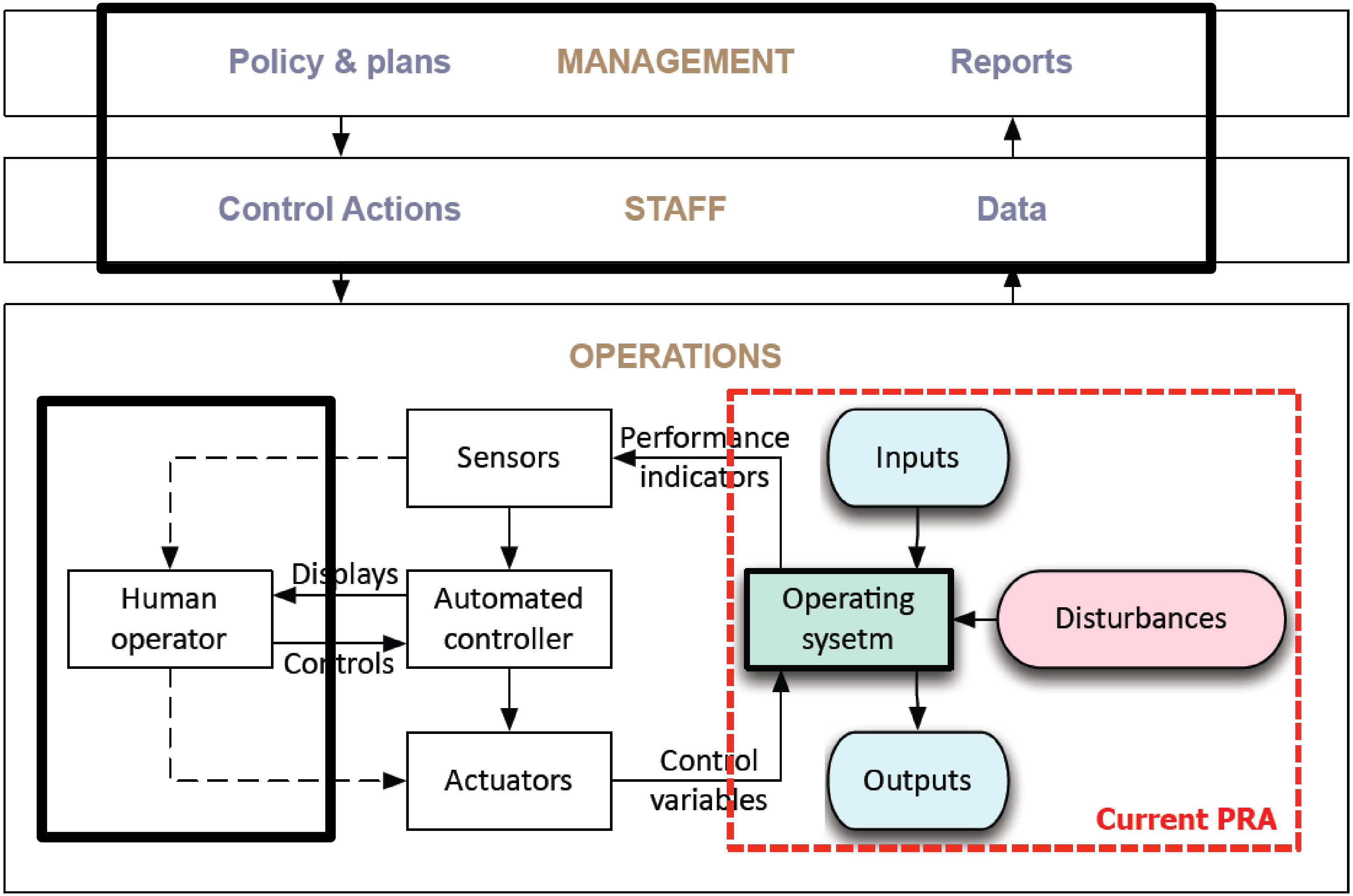
Adapted from Leveson, 2010 , Baecher, 2014

SYSTEM DYNAMICS SIMULATION

Operations Sector:

- Operational decisions (errors)
- Inflow forecast accuracy
- Maintenance budget
- Maintenance activities
- Local staff availability and qualifications
- Component priority (manufacturers maintenance recommendations, risk acceptance)
- Changing values (eg. environmental, regulatory, First Nations)

SYSTEM DYNAMICS SIMULATION



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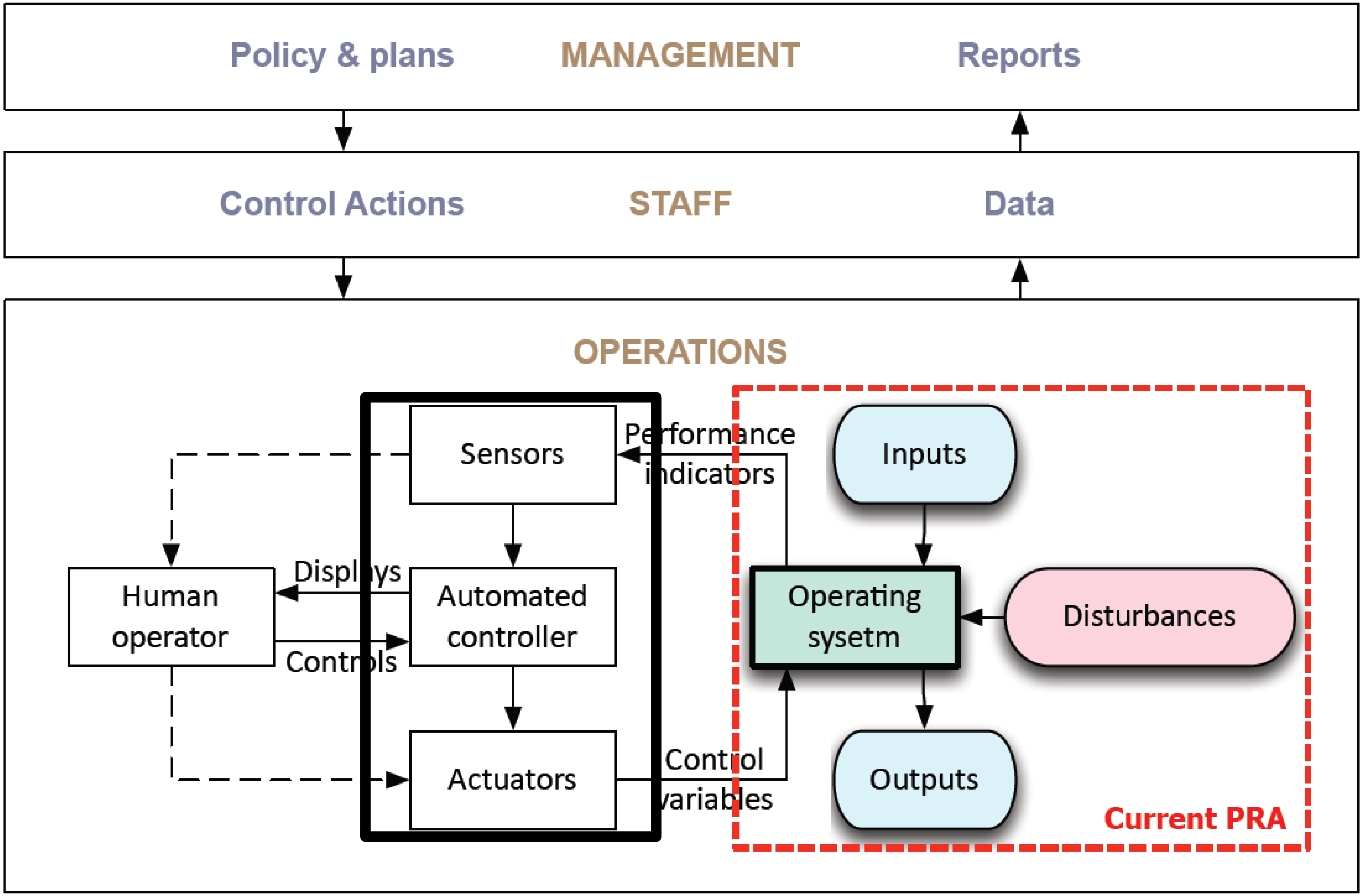
SYSTEM DYNAMICS SIMULATION

Information Flow Sector:

- Accuracy and values from gauges measuring:
  - Reservoir level
  - Landslide movement
  - Embankment dam seepage
  - Penstock leakage
  - Forces on spillway gate hoists, etc.
- Gauge condition
- SCADA Systems (relay of sensory information to operators, alarms)
- Communication systems (microwave, radio, etc.)

SYSTEM DYNAMICS SIMULATION



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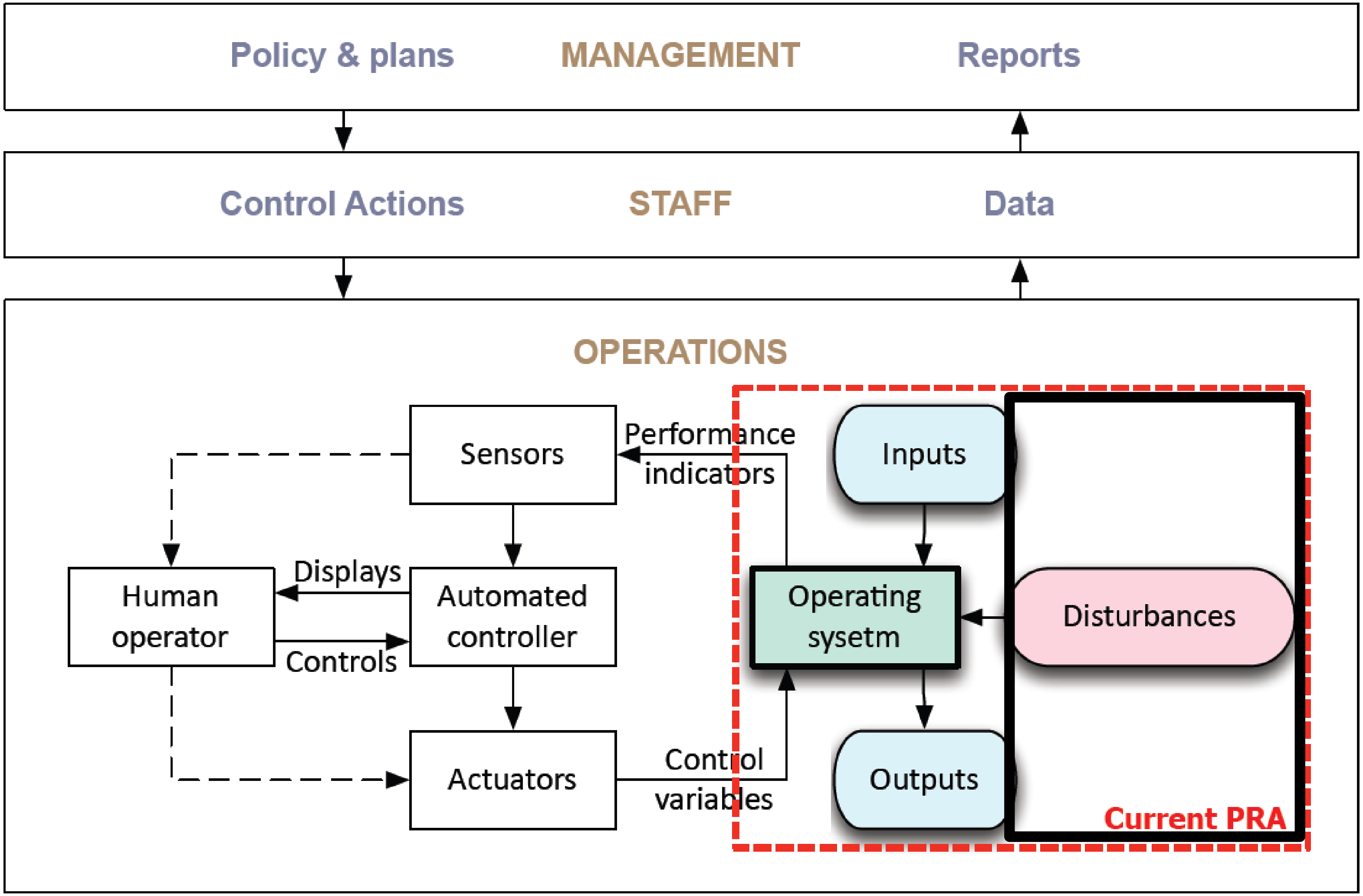
SYSTEM DYNAMICS SIMULATION

Disturbances Sector:

- Earthquakes
- Landslides
- Rockfalls
- Sinkholes
- Floods (stochastic timeseries input?)
- Forced outages (turbines, generators, electrical equipment, spillway gates, etc.)
- Debris buildup (affecting spillway capacity, ability to operate gates, ability to inspect dam face)

SYSTEM DYNAMICS SIMULATION



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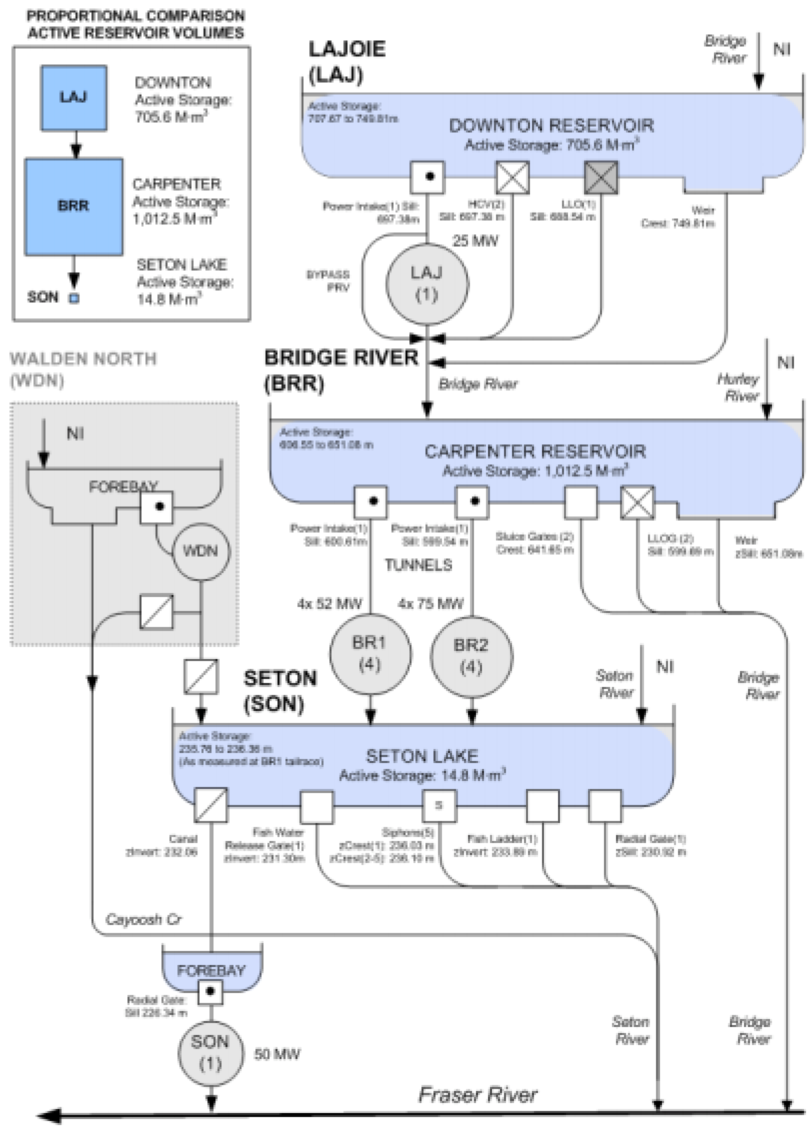
SYSTEM DYNAMICS SIMULATION

Next steps in creation of a working example:

- Research partnership between BC Hydro and Western University (Civil Engineering)
- Application to NSERC's Collaborative Research and Development grant program
- Development of theoretical foundations that will help quantify relationships in the system dynamics simulation model
- Application of simulation approach to BC Hydro's Bridge River system

BRIDGE RIVER



RELIABILITY OF FLOW CONTROL SYSTEMS

Possible benefits of system dynamics modelling for flow control systems:

- Representation of extremely complex, nonlinear systems in a computational model
- Consideration of factors beyond physical structure of a system
- Identification of critical system components with respect to dam safety and overall system reliability
- Ability to test different system configurations to assist in decision making for capital upgrades
- Modeling of budget and staffing for sensitivity analysis of budget cuts
- Training of future system operators in a safe environment

RELIABILITY OF FLOW CONTROL SYSTEMS

Questions?